Development and Modeling of Angled Effusion Cooling for the BR715 Low Emission Staged Combustor Core Demonstrator

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Abstract

A technology program was started in 1994 within the framework of the German Aeronautics Research Program to develop axial staged combustor technology up to a core engine demonstrator. The objective was to demonstrate a 50% NOx reduction against the ICAO CAEP II limit without any compromise on the CO, UHC and smoke emission level compared to the latest single annular combustor technology. All other requirements, like ignition and relight capability, stability, durability and turbine inlet temperature traverse, were set equal to today's state-of-the-art combustors.

The combustor cooling concept chosen was of the angled effusion type. Development of adequate modeling techniques and steady-state and transient rig tests to calibrate the thermal models was the key factor for the success of the project. Despite the 15% increase in cooled surface, the overall combustor flow fraction required for cooling was reduced by 15% without any change in the combustor liner material from that of the in-service single annular combustor of the BR715.

The axially staged combustor technology developed in the described program enables RR Deutschland to offer a staged combustor for the BR715 within the usual timescale of an engine certification process. It also forms the basis for future combustor technology to limit NOx-emissions for advanced engine cycles.

Nomenclature

A_{geom}	Geometric coolant flow area
AFR	Air fuel ratio
CAEP	Committee on Aviation Environmental Protection
c_D	Discharge coefficient
CFD	Computational Fluid Dynamics
FE	Finite Element
HTC	Heat Transfer Coefficient
ICAO	International Civil Aviation Organisation
N2	HP-shaft speed
P	Porosity
$T_{hot-wall}$	Surface temperature on hot side of wall
T_{gas}	Temperature of hot combustion gas
$T_{coolant}$	Temperature of cooling air
η	Total cooling effectiveness

1. Introduction

With increasing air traffic, intensive research work on potential climate changes has been initiated. Recent studies [1] indicate an increase of NOx concentrations of approximately 30% by aviation in the main northern hemisphere flight corridors (8-12 km altitude) which might induce an ozone increase of 4%. By this and in combination with CO_2 emission the green house effect tends to be augmented. Therefore, the aero-engine industry is working on technologies to reduce the emissions level as a precautionary principle. The international emissions regulations were established by ICAO, which decided a further increase in stringency for new engines after 31st December 2003 (CAEP IV), see figure 1. Furthermore, through local airport emission charges like Zürich or Geneva and all major

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Swedish airports, the direct operating costs of commercial transport are influenced by the combustor technology and the customers request further reductions in emissions beyond certification limits [2].

A key factor in reducing NOx emissions is the redistribution of the combustor air mass flow. More air for the fuel injectors and mixing ports allows better control of the fuel preparation and combustion process, enabling the required reduction of the NOx production. Since the mass flow through the combustor module stays constant for a given engine cycle and the secondary air flow requirements of the following engine modules will not be reduced, less air is available for combustor cooling purposes when introducing low NOx combustor technology. Figure 2 shows the development of the air mass flow split through the combustor for three different configurations. The datum single annular concept is the in-service BR715 combustor, the cross section can be seen in figure 3. The middle column of figure 2 represents the axial staged combustor discussed in this paper. Figure 4 shows a cross section of this combustor, as used in the core demonstrator. Due to the separation of pilot and main combustion zone, the surface area, which needs to be cooled, is increased by 15%. The staged combustor concept has to cope with a 15% reduction of the cooling air compared with the datum configuration due to changes in the fuel preparation strategy. In the future, lean burn concepts might be used, which need up to 80% of the combustor mass flow for the fuel preparation and mixing, leading to an even greater reduction in available cooling air.

In addition to this, advanced engine cycles tend to use higher pressure ratios, associated with higher compressor outlet temperatures and/or higher bypass ratios, hence lower AFRs in the combustor and therefore increased turbine inlet temperatures. These trends require the development of cooling techniques far beyond the capability of conventional cooling devices.

2. Concept analysis

Four major concepts for cooling the combustor liner investigated were:
- The large group of well known cooling rings:
  - rings fabricated from sheet metal
  - rings machined from forgings
  - with or without a lip on the hot side
  - holes drilled by laser or electro discharge machining (EDM)
- Single skin effusion cooling
- Tiles on a carrier liner
- Transpiration cooling sheets

Single skin effusion offers a good combination of reasonably high cooling effectiveness (compared with cooling rings), low weight (compared with tiles) and ease of local cooling adaptation i.e. for hot spot treatment (compared with transpiration cooling sheets). But the knowledge about the cooling capability and the proper modeling of single skin effusion was not sufficient at the beginning of the development program.

A preliminary design study was carried out based on an analytical model for the cold side convective cooling, the internal heat pick-up and the hot side film cooling. Based on this model the following main parameters were selected for the development program:

- Effusion hole diameter
- Surface angle
- Compound angle η
- Porosity
- Wall thickness
- Wall pressure drop

The quantities used to characterize a cooling configuration were porosity and total cooling effectiveness, as defined by:

$$P = \frac{c_D \times A_{geom}}{A_{wall}} \qquad \eta = \frac{T_{gas} - T_{hot-wall}}{T_{gas} - T_{coolant}}$$

The principle relation of wall porosity and total cooling effectiveness for a specific effusion cooling configuration is displayed in figure 5. A power law ($\eta = A*P^B$) is used to represent the result of the

analytical investigation. The relative contribution of the different heat transfer modes was also studied. The result for a typical configuration is given in table 1.

Table 1: Relative contribution of heat transfer modes to the total cooling effectiveness of a typical configuration

Mechanism	Contribution
Film cooling on hot surface	≈30%
Internal heat pick-up in effusion holes	≈40%
Cold side convective cooling	≈30%

The further development of the effusion cooling design is strongly linked with the experimental verification, as described in section 3, which led to a concurrent development of the cooling technique and the associated modeling techniques.

3. Modeling of effusion cooling

To model effusion cooling at specific parts of the combustor in an FE analysis, several boundary conditions must be known at each location: the coolant and gas temperature on both sides of the combustor liner, the radiative heat flux to the wall and the local pressure drop across the wall. To have access to this information during the complete flight cycle, a transient 1D network representation of the air flow around and through the combustor is coupled within the FE analysis model.

Based on the knowledge about the combustor design and the flow structure, appropriate heat transfer correlations are applied to each surface. Basic heat transfer correlations are available within the FE analysis program. If the flow structure is too complex for simple correlations, CFD is used to calculate a heat transfer pattern. The generated pattern is then applied to the surface under investigation. An example for such an approach is given in figure 6, where the effusion air streams form a complex cooling effectiveness and heat transfer pattern on the hot side of an effusion cooled wall. In a locally resolved wall temperature calculation, this variations can not be ignored. Based on the CFD results, a general HTC pattern was derived. Additionally, a correlation was built to represent the dependency of the mean HTC in the pattern on the specific operating condition like combustor inlet pressure, temperature and mass flow.

To get the transient 3D temperature distribution in the combustor liner, which was the basis for a lifing procedure, a comprehensive modeling process had to be completed. Figure 7 gives a schematic overview of this process. First a 2D model of the complete combustor module (see figure 4) was developed, which included inner and outer casings, compressor outlet guide vanes and turbine nozzle guide vanes. A data base provides all the necessary material data used in the analysis. Engine performance data and the specific flight mission cycle under investigation are fed into the calculation during the analysis. This complex setup is then matched with thermal paint results and with thermocouple measurements taken during engine testing.

The result at a specific time instant of a transient 2D simulation is displayed in figure 8. The colder casing around the hotter combustion chamber is visible, as well as the relatively hot fuel injector heat shields and the nozzle guide vanes.

The 3D model of the combustion chamber is now embedded in the 2D module to get the time-depended temperature distribution on the model interfaces like the combustor mounting flange. For this analysis mainly the thermal paint results are used to get the correct temperature variations in the circumferential direction. The result of such a transient 3D analysis is displayed in figure 9. For a specific time instant shortly after a strong increase in fuel flow, the flange is still relatively cold, but the low AFR in the primary zone resulting in a strongly radiative flame leads to a hot region near the mixing ports of the main zone with significant temperature variations in circumferential direction.

4. Experimental program

To verify the analytical findings and to match the transient FE analysis, an extended experimental program was carried out.

As a first step, several thermal paint test with effusion cooled panels were performed in a 90 degree sector rig using the test facility of DLR Köln. Inlet pressure P30 is restricted to 2000 kPa whereas inlet

temperature T30 and air-fuel-ratio (AFR) were set to realistic engine conditions. The inlet of the rig was represented by a pre-diffuser to provide a representative flow field in the annuli of the combustor. The rig was instrumented with total pressure rakes, static pressure tappings and thermocouples for monitoring the inlet conditions and external effusion panel temperature. Both sides of the effusion panels were covered with a temperature sensitive paint selected to resolve the expected temperatures on the respective surface. The flow through the nozzle guide vanes and into the secondary air system was simulated by appropriate orifices at the combustor exit.

The design of the cooling panels was based on the analytical model described in the previous section. Four panels were tested at the same time. This setup was used to study the influence of the basic effusion pattern, surface angle and compound angle on hot side surface temperature, wall temperature gradient, and observed hot spot size. The findings were fed back into the design tools and were used to calibrate the transient calculations.

The next step was to apply the knowledge gained and the now improved design and analysis tools to a staged combustor. Several staged combustor cans were instrumented with thermocouples and coated with temperature sensitive paint on both sides. The tests were again performed at DLR Köln. A typical setup is displayed in figure 10. The results were used to adapt the effusion hole pattern to the local cooling requirements, to actively cure hotspots and to further refine the manufacturing techniques. The first staged combustor had a porosity slightly higher than the required level according to the prediction. Then step by step the porosity was reduced based on the thermal paint results, shifting more and more air to the fuel preparation process. Figure 11 shows the result of a thermal paint test on a 90 degree sector can. The temperature distribution on hot and cold side is relatively homogeneous and well within the material limits. The findings were used to further refine the aforementioned models.

As a final check full annular tests were carried out. The thermal paint indicated little circumferential temperature variation and a safe mean metal temperature. Therefore, a similar can was mounted in the core demonstrator.

5. Core demonstrator

The effusion cooled combustor was integrated in a BR700 core engine which included a 10-stage HP compressor and a 2-stage HP-turbine. The core engine was tested in the altitude test facility (ATF) of Technical University Stuttgart. The LP system (fan, booster, LP-turbine) of the engine was simulated by an appropriate level of pressure, temperature and mass flow delivered by the air-station. A computer control system coordinates the operation of the core engine and the facility, which enables as well transient maneuvers. The control system is described in more detail in [3].

The combustor was coated with a temperature sensitive paint. Furthermore, the combustor liner temperatures were measured at 13 locations with thermocouples embedded in the outer surface. Additional thermocouples were embedded in the rear combustion chamber mounting flange and in the combustor outer casing. Air stream temperatures around the outer casing were also measured. A radiation probe was fitted in the combustor outer casing and positioned just above a mixing port of the main zone. After each test run the hot section was boroscoped and the change of the color of the thermal paint was correlated against the running condition.

Starting the engine was done by wind-milling at 15-20% N2 and after ignition the core was accelerated to idle speed in pilot only mode. Then the engine was set to a specific operating condition representing a part of the mission flight cycle. After the temperatures reached steady state, the output of all the above mentioned thermocouples was averaged over a longer time. For the transient thermal survey, the engine was accelerated from idle to take-off condition in different time spans, kept at high thrust for a specific duration and then decelerated back to idle. The transient behavior of combustor pressure, inlet temperature, mass flow and primary zone radiation and the response of all the above mentioned thermocouples was recorded. These transient experiments were used to calibrate the transient thermal FE model.

The thermal paint was analyzed in detail when the core engine was stripped. No integrity problems were observed. The temperature field on the combustor liner was overall quite homogeneous with a

slight periodic deviation for every main burner position, but still within the safe operation limit for the liner material. The following emissions were documented:

- NOx: 51% CAEP II ICAO Limit
- CO: 20% ICAO Limit
- UHC: 2% ICAO Limit

Also the smoke number was comparable to the datum BR715 engine. The emission results are discussed in detail in [4].

6. Conclusions

Analytical modeling with post-test matching was used as the basis of the cooling design process. This approach led to a concurrent development of the cooling technique itself and the associated modeling technique. Embedding 3D FE models into 2D models was found necessary to derive the appropriate time-depended boundary conditions on model interfaces. For complex situations, like the heat transfer on the hot gas side in the presence of effusion cooling, coupling of CFD and FE analysis was successfully applied to derive the local HTC pattern.

The careful approach of first testing single panels, then step by step reducing the cooling air in the 90 degree sector rig led to a successful run of the core demonstrator without any integrity or overheating problem of the staged combustor throughout the development program.

The staged combustor cooling air was reduced by 15% compared with a datum BR715 single annular combustor despite the increase of 15% in cooled surface without a wall material change. The observed liner temperature still lies within the limits for long durability. The large number of thermocouple and radiation data collected during the core run was used to further refine the thermal modeling.

For future more advanced thermodynamic engine cycles compared with that of the BR715 or a more stringent NOx reduction requirement, the air used for wall cooling must be optimized, i.e. new cooling technologies or materials for the liner wall must be introduced. In the long term, premixed combustion in the main zone offers a method to further reduce NOx and to lower the heat load on the heat shields and liner walls. Intensive research work on new cooling techniques for lean premix combustion is going on in extension to the work presented in this paper.

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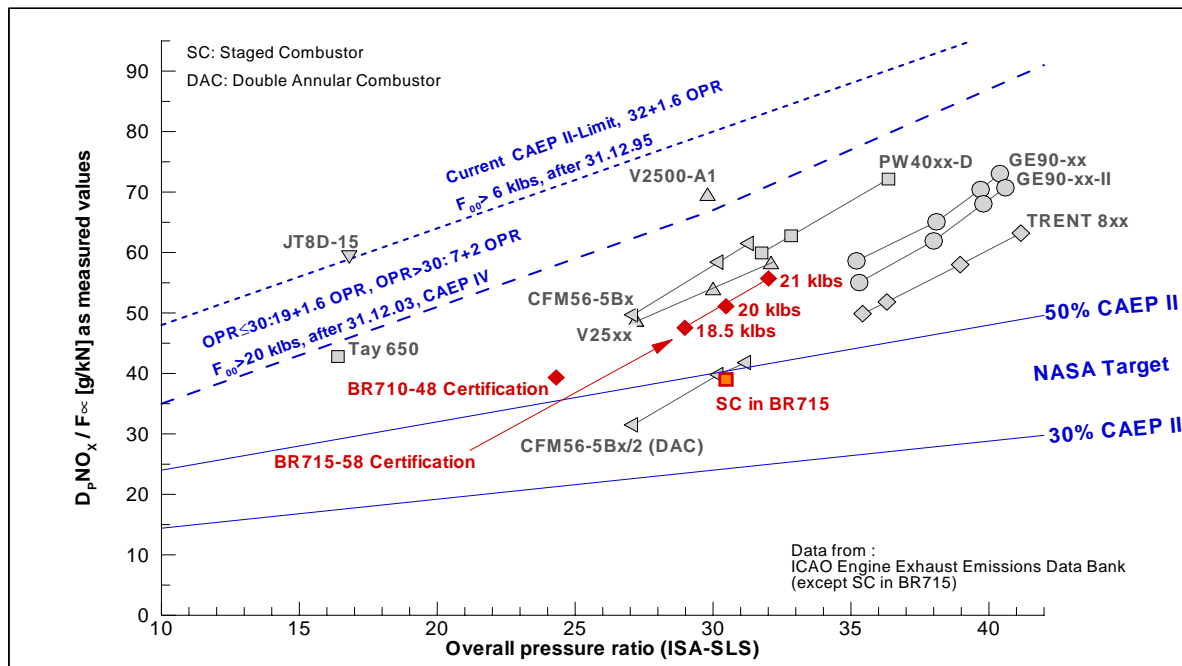
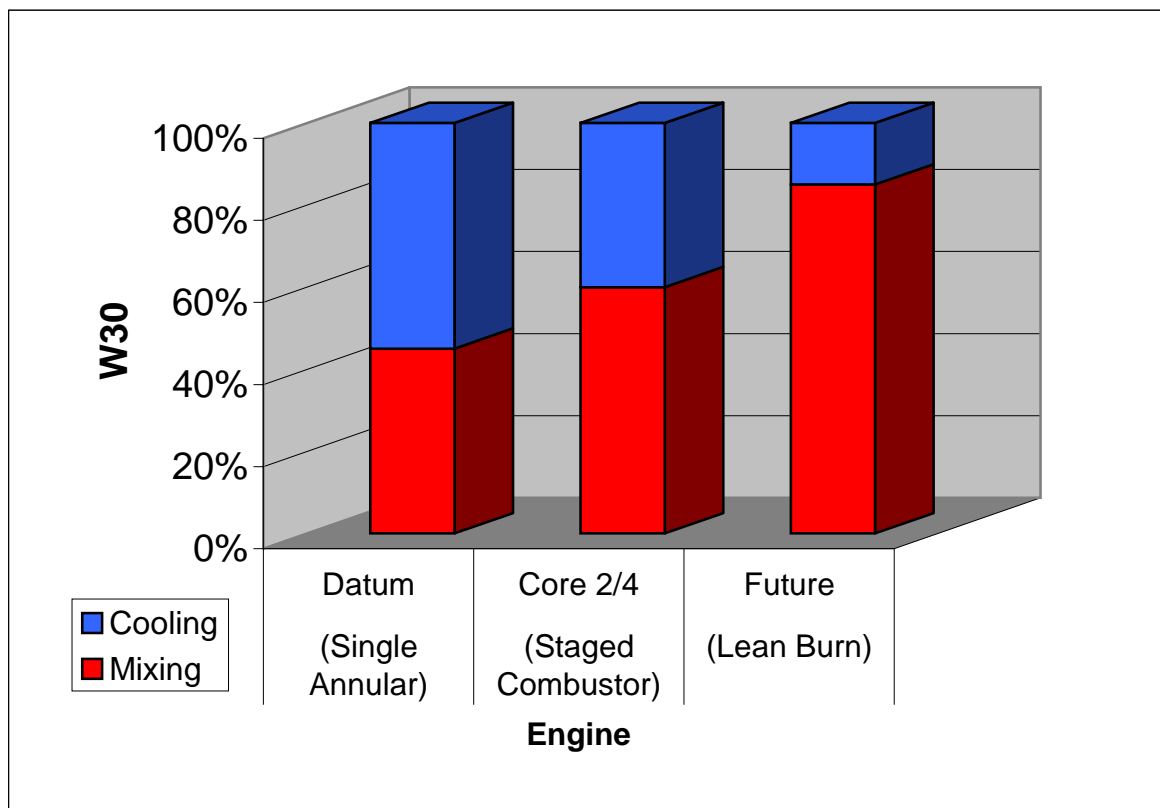Figure 1: NOx emissions according to ICAO regulation

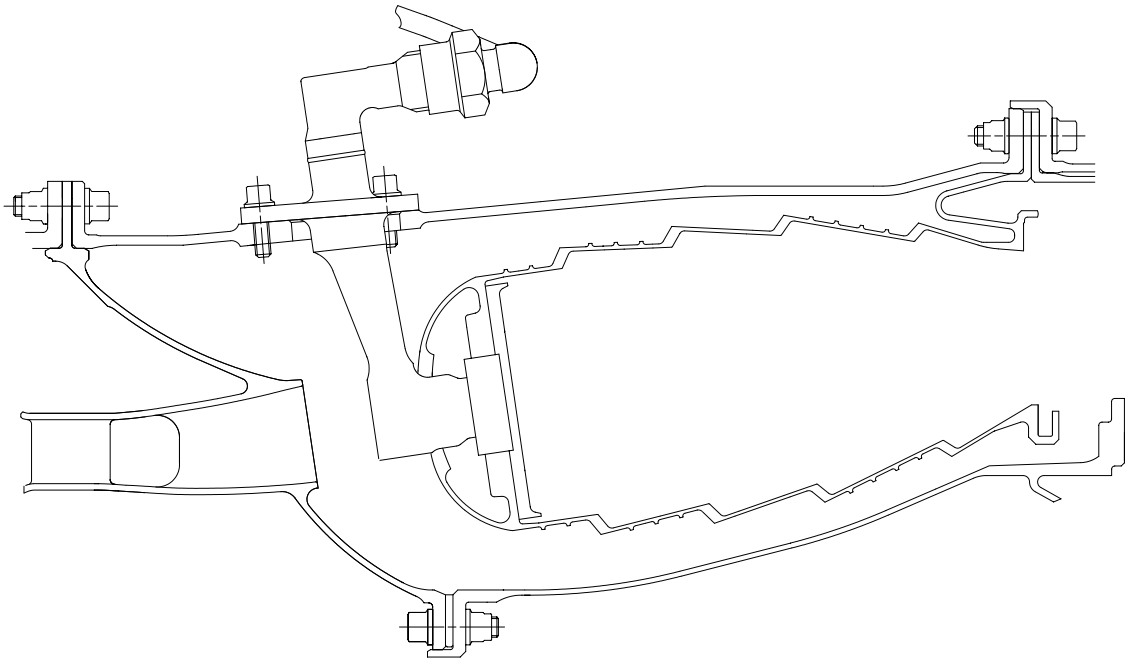Figure 2: Development of the air mass flow split

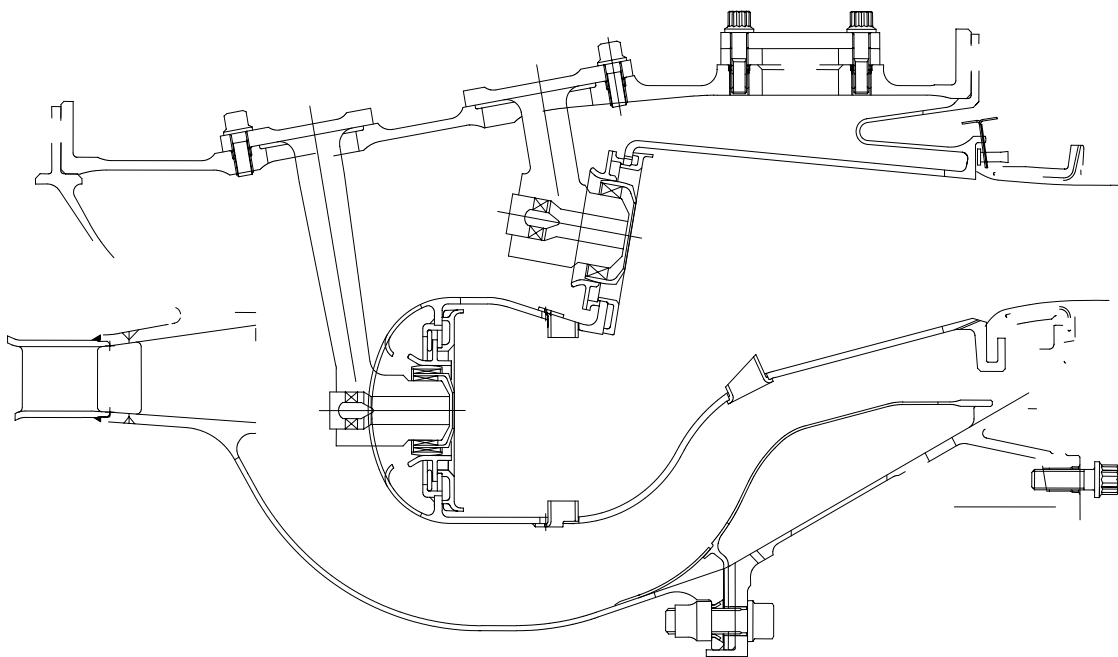Figure 3: Composite section of datum combustor

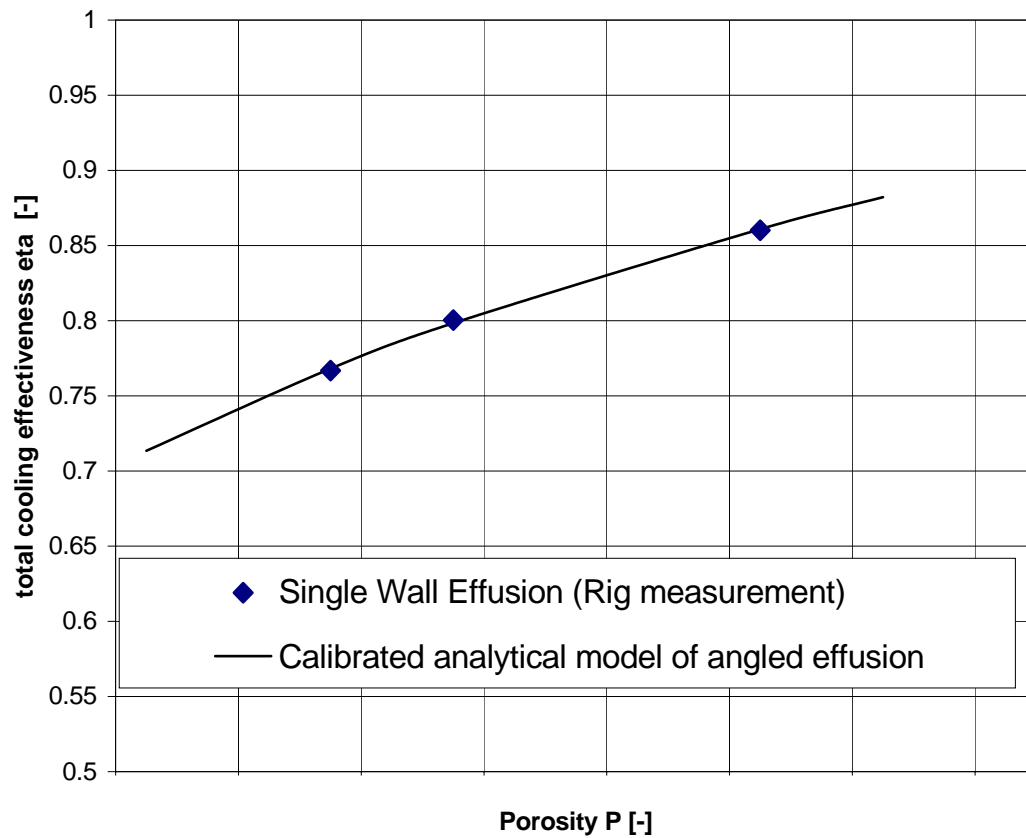Figure 4: Composite section of staged combustor

Figure 5: Total cooling effectiveness vs. wall porosity for single skin effusion
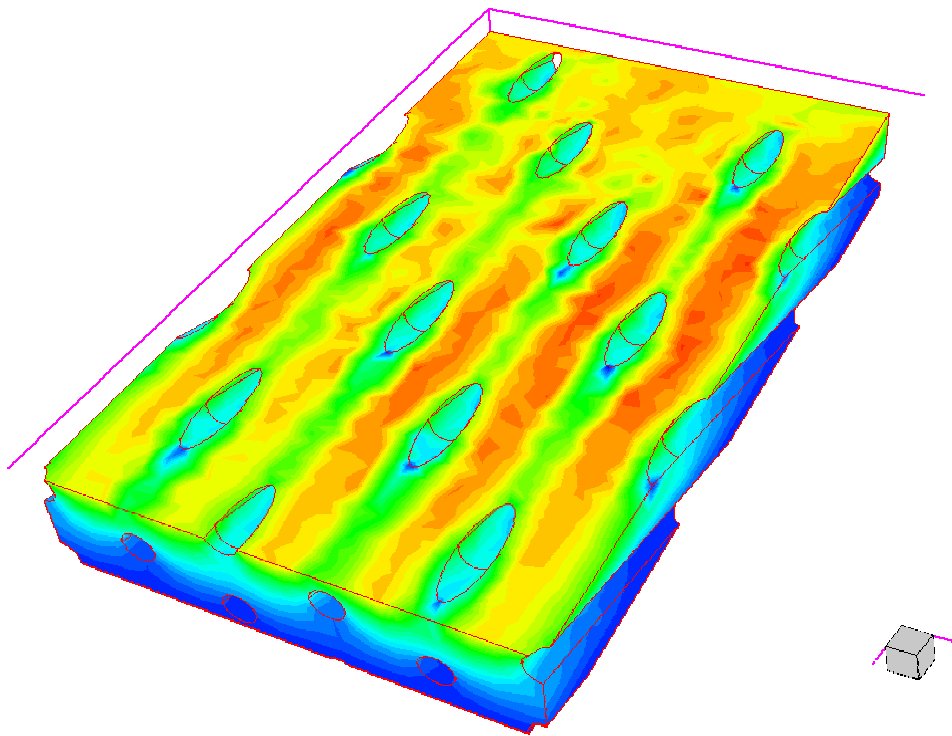

Figure 6: 3D model of effusion cooled wall with CFD derived HTC pattern

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│      3D transient             │
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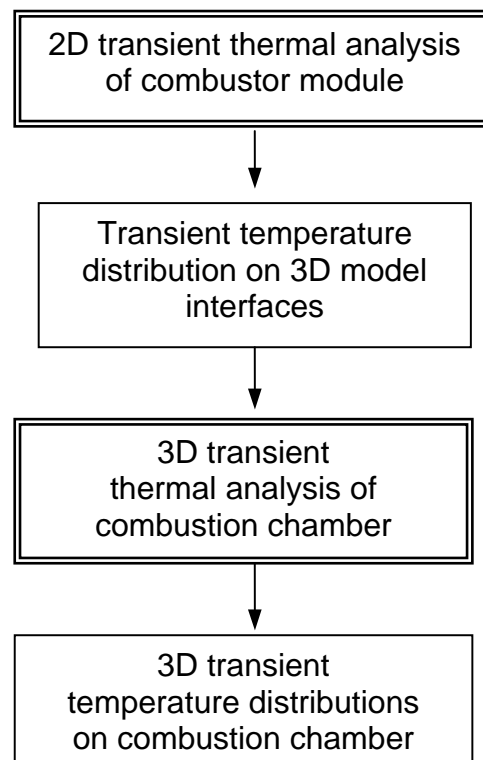
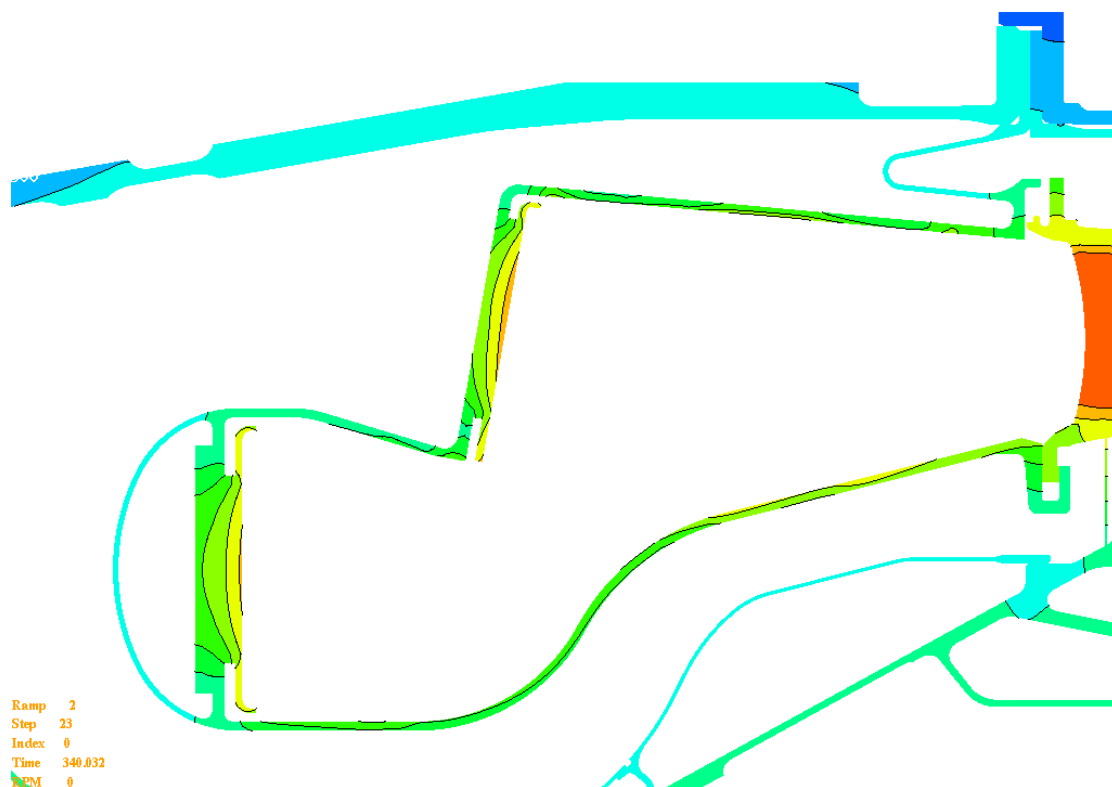Figure 7: Flow Chart of general modeling procedure

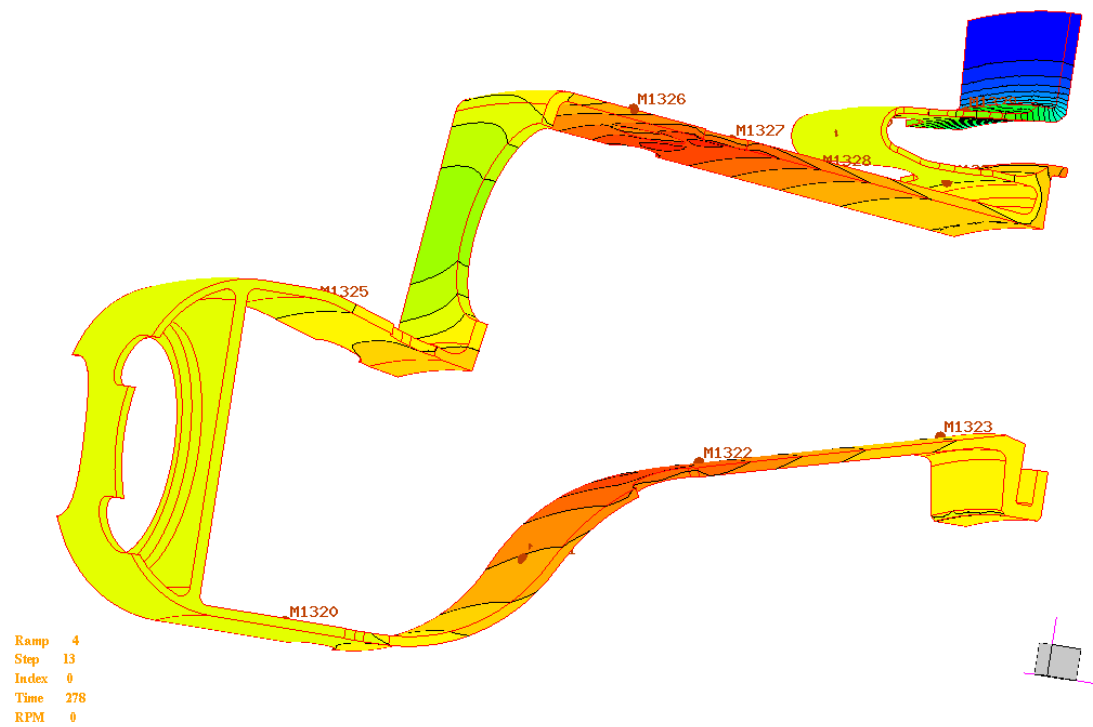Figure 8: 2D model of staged combustor module with heatshields

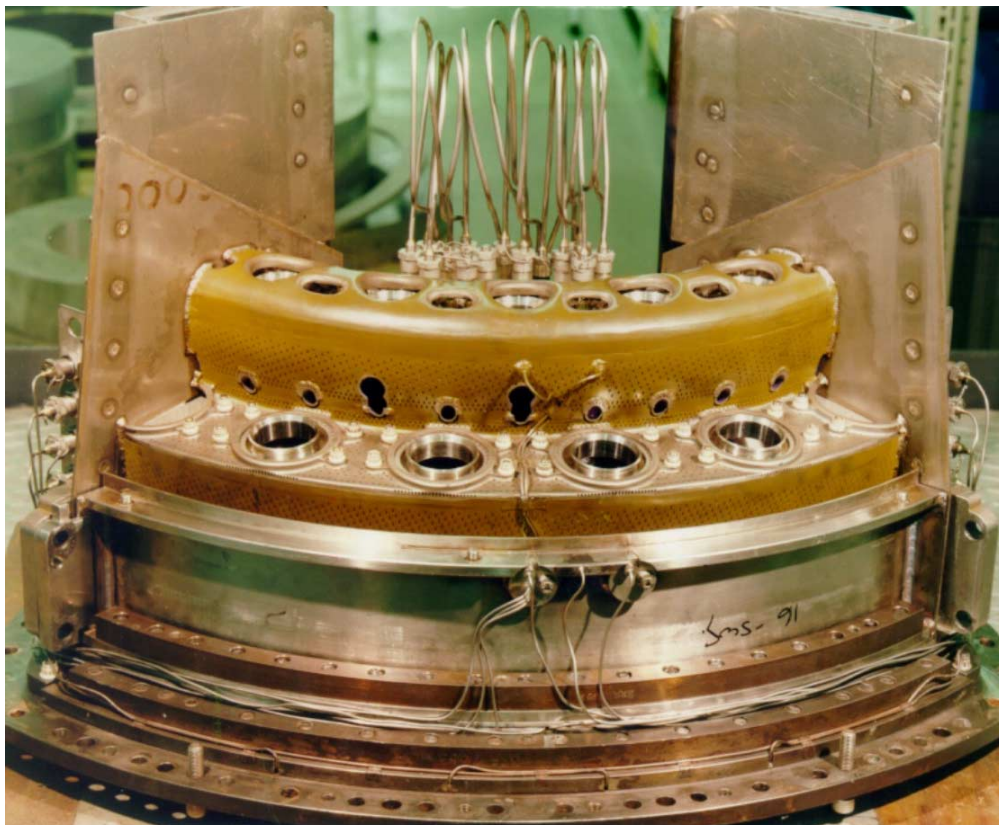Figure 9: 3D model of staged combustor without heatshields
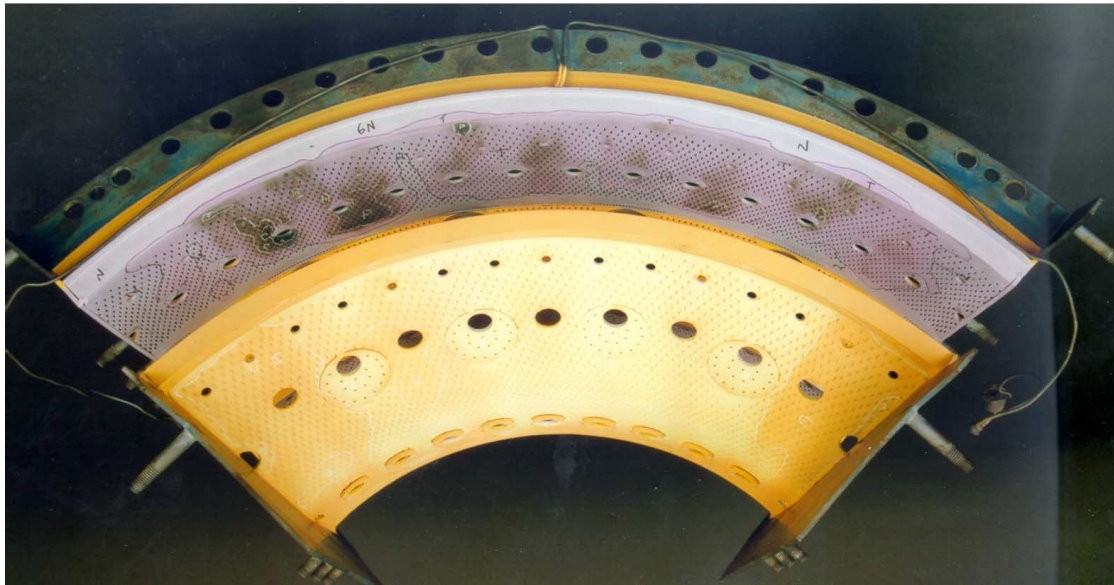

Figure 10: High Pressure 90 degree combustor

Figure 11: Thermal paint on 90 degree sector

Paper Number: 11

Name of Discusser: H. Weyer, DLR Cologne

Question:
How did you model turbulence in the neighborhood of the holes within the 3 D-analysis of flow and heat transfer?

Answer:
Fluent with standard K- Ξ turbulence model was used.

Name of Discusser: B. Simon, MTU Aero Engines Munich

If I compare the situation of the combustor with that of airfoils. In terms of air foils one is switching from cylindrical holes to fan shaped holes to improve the coverage of the cooling air.
Combustors are going from conventional cooling films which distribute the cooling air in transversal direction much better to cylindrical holes.
What is the reason that you save at the end 15 % cooling air with effusion cooling?

Answer:
a) the sum of all effusion holes represent a quite large heat transfer surface.
b) The cooling film on the hot side is steadily refreshed. Both facts lead to a total cooling effectiveness, which is higher than the one of conventional injection film cooling.